Charmonium production in pp, pA and AA collisions

Puzzles and solutions

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Outline

- **pp:** mechanisms of J/ψ production vs data

- **pA:** leading/high twist shadowing, saturation, color transparency, etc.

- **AA:** puzzling behavior of $R_{AA}^{J/\Psi}(p_T)$; charmonium as a probe for the dense matter; transport coefficient from J/ψ suppression

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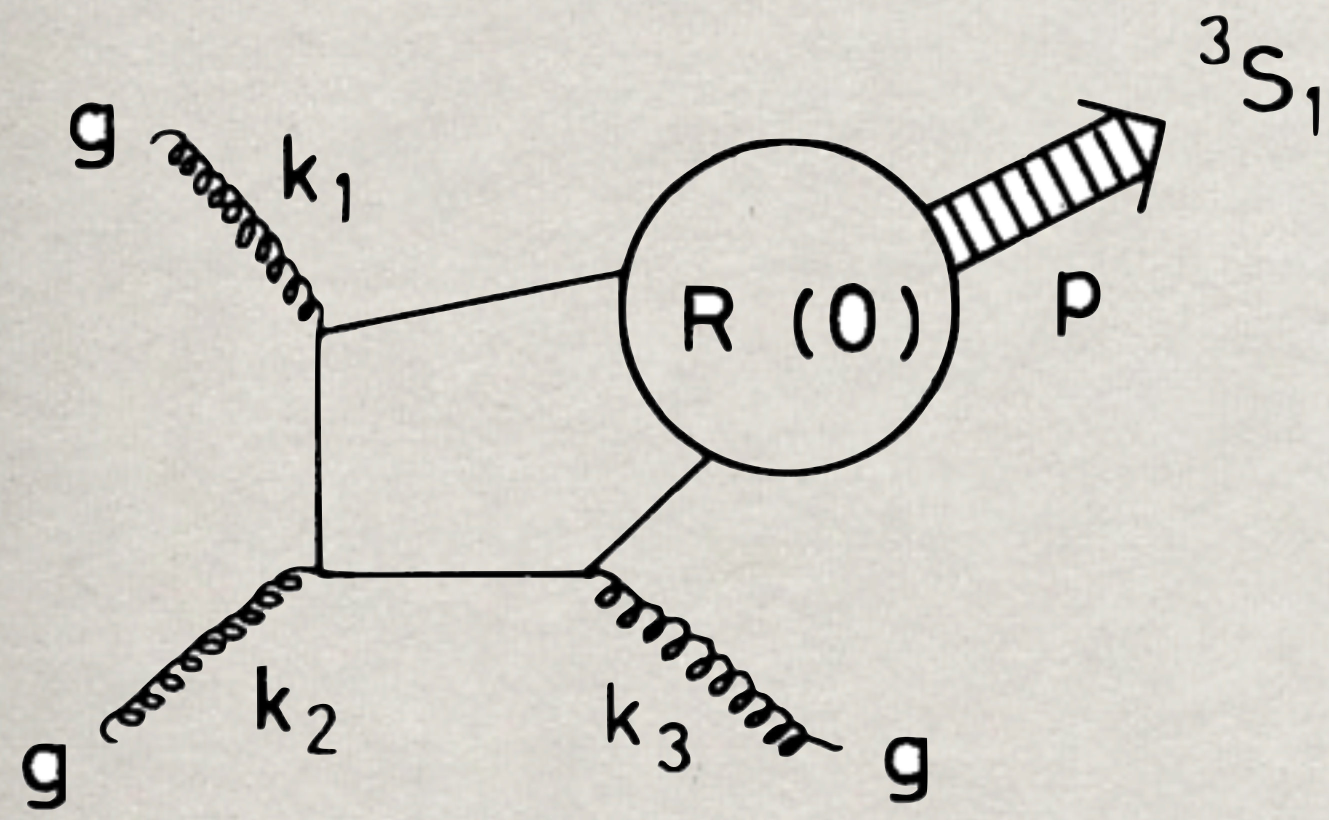
Understanding pp data

Color singlet mechanism



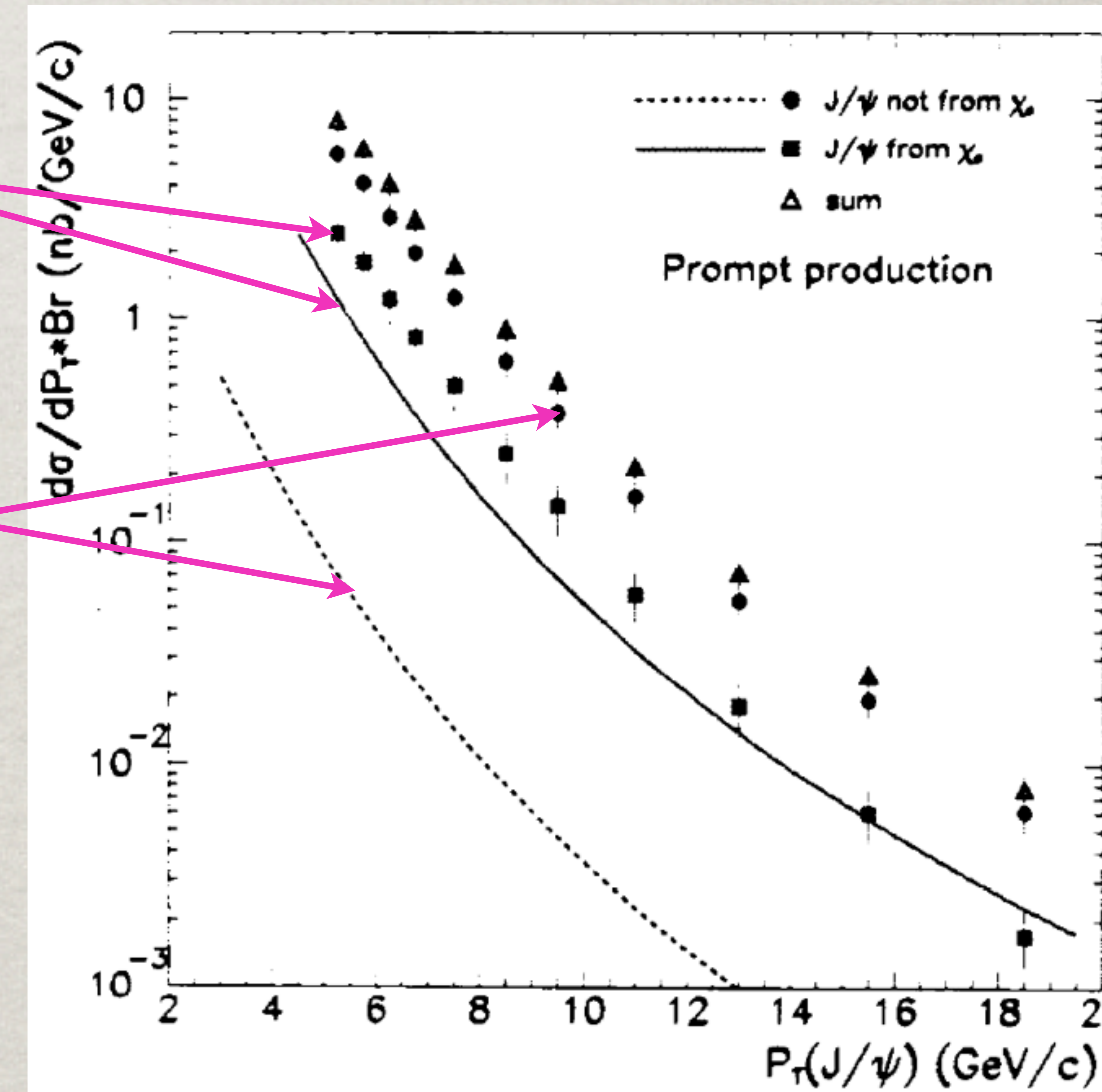
E.Berger & D.Jones (1980)
R.Baier & R.Ruckl (1981)
} collinear factoriz.

Ph.Hagler, R.Kirschner,
A.Schaefer, L.Szymanowski, & O.Teryaev (2001)

k_T factorization

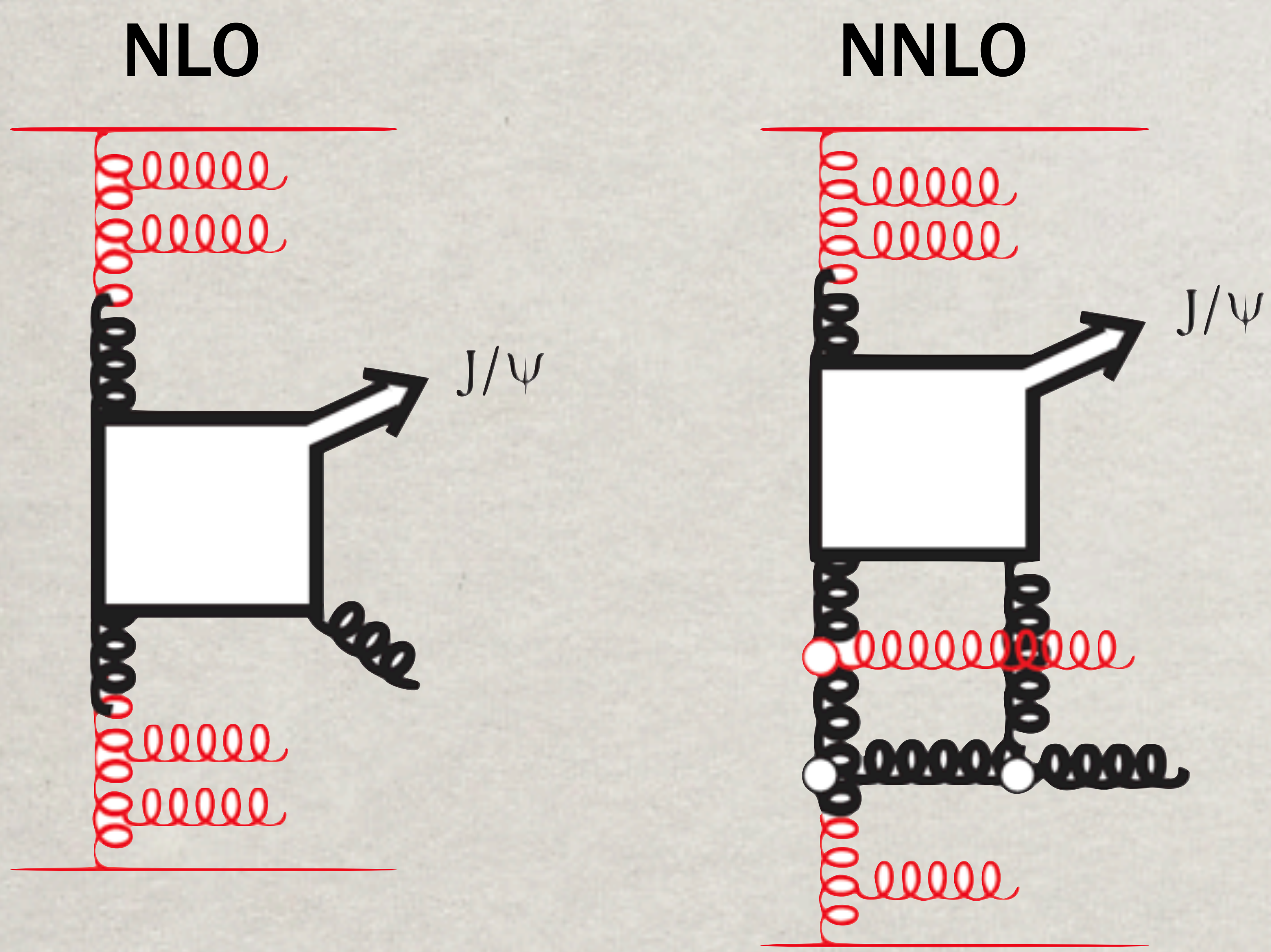
from χ

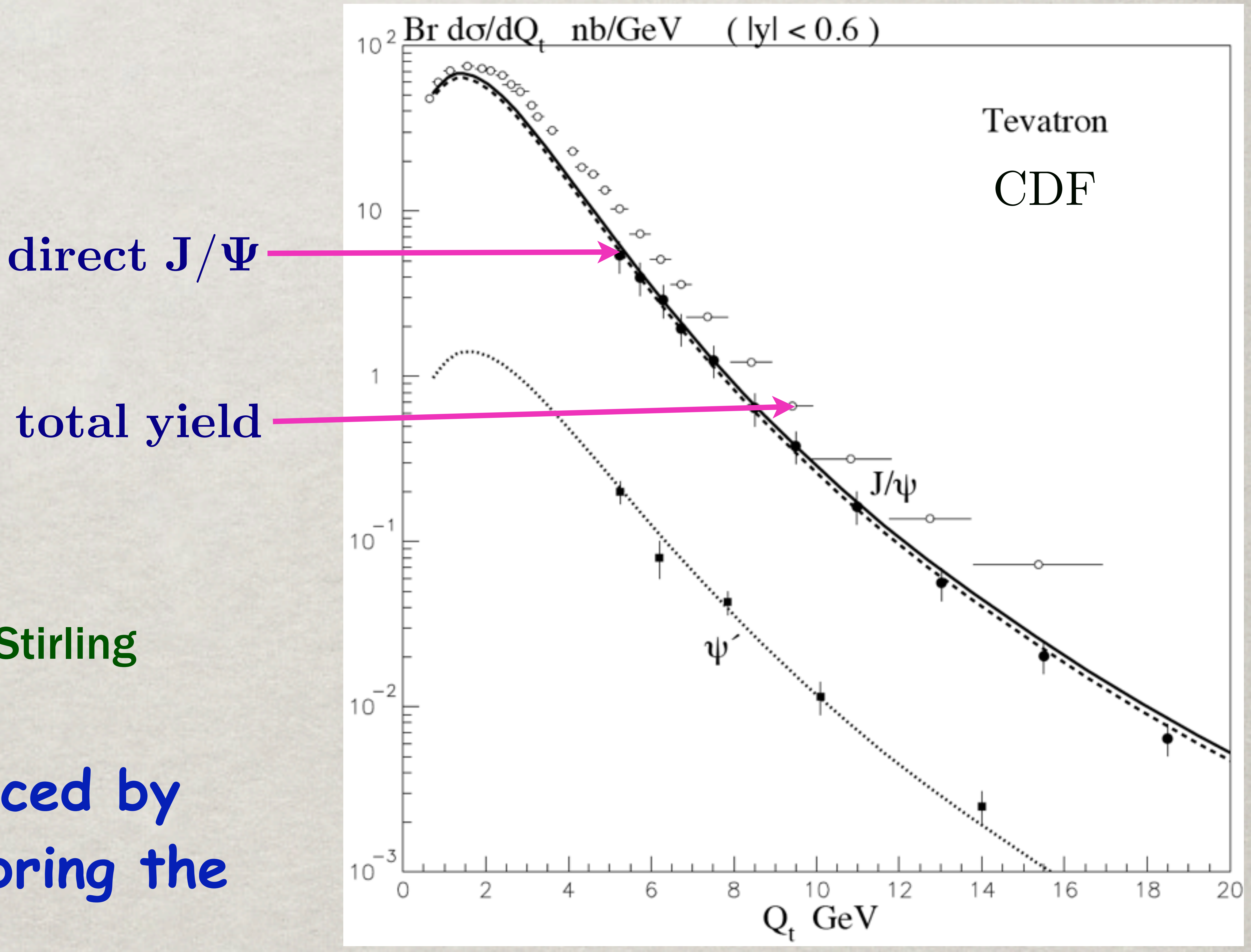
direct J/Ψ



Understanding pp data

Modified color singlet mechanism

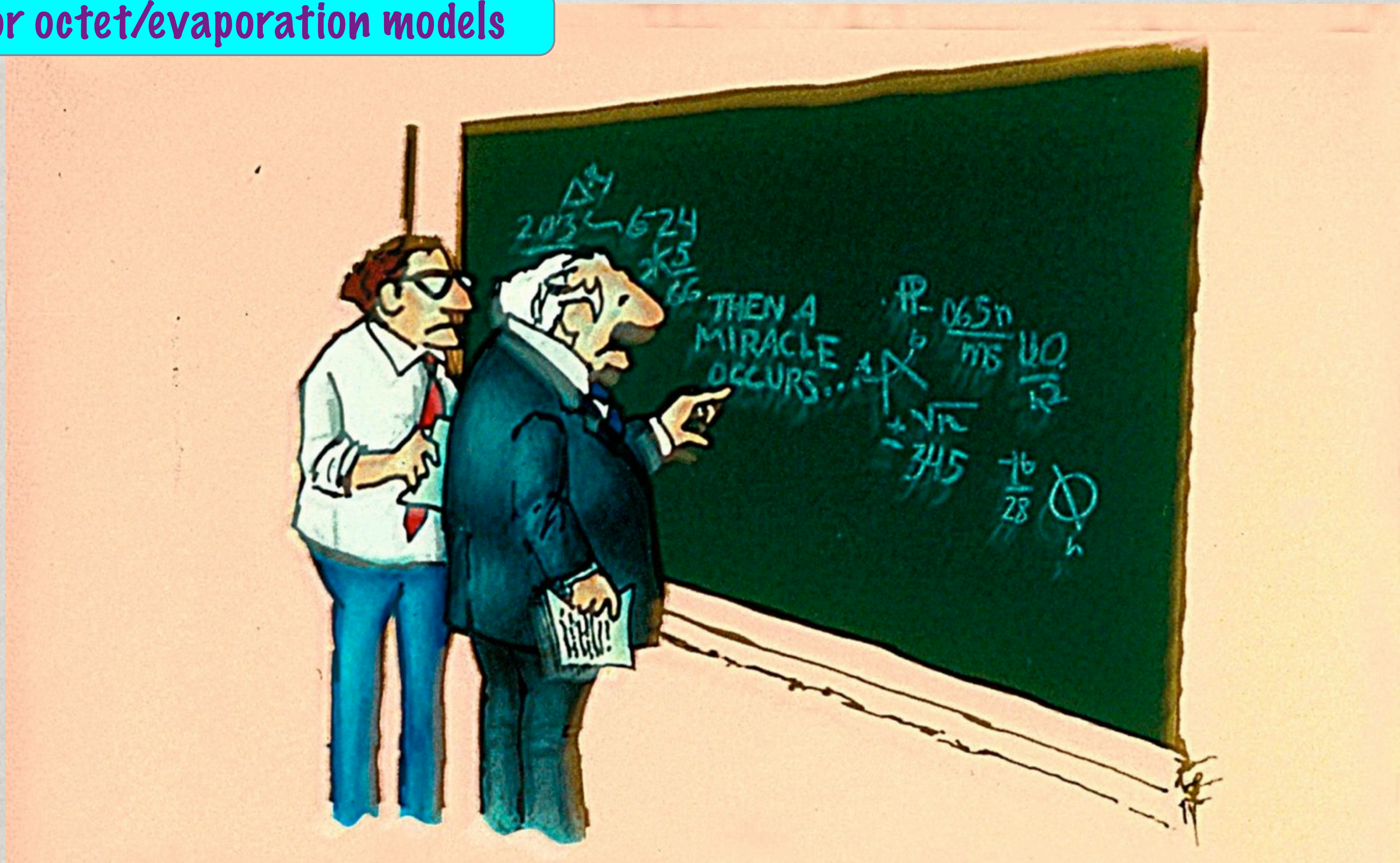




V.A. Khoze, A.D. Martin, M.G. Ryskin and W.J. Stirling (2004)

The NNLO contribution is enhanced by the factor lns, which allows to bring the cross section up to the data.

Color octet/evaporation models



"I think you should be more explicit here in step two"

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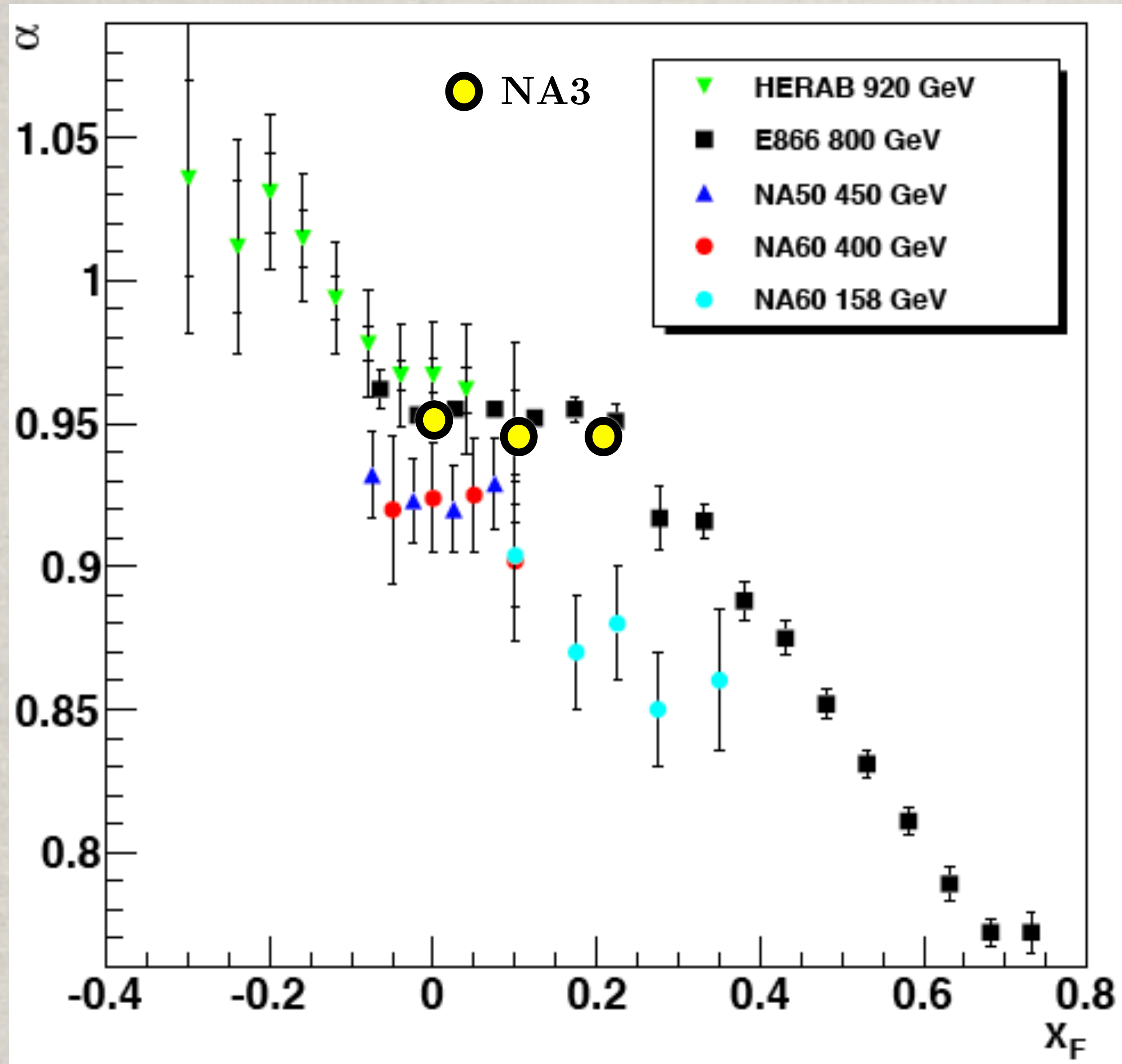
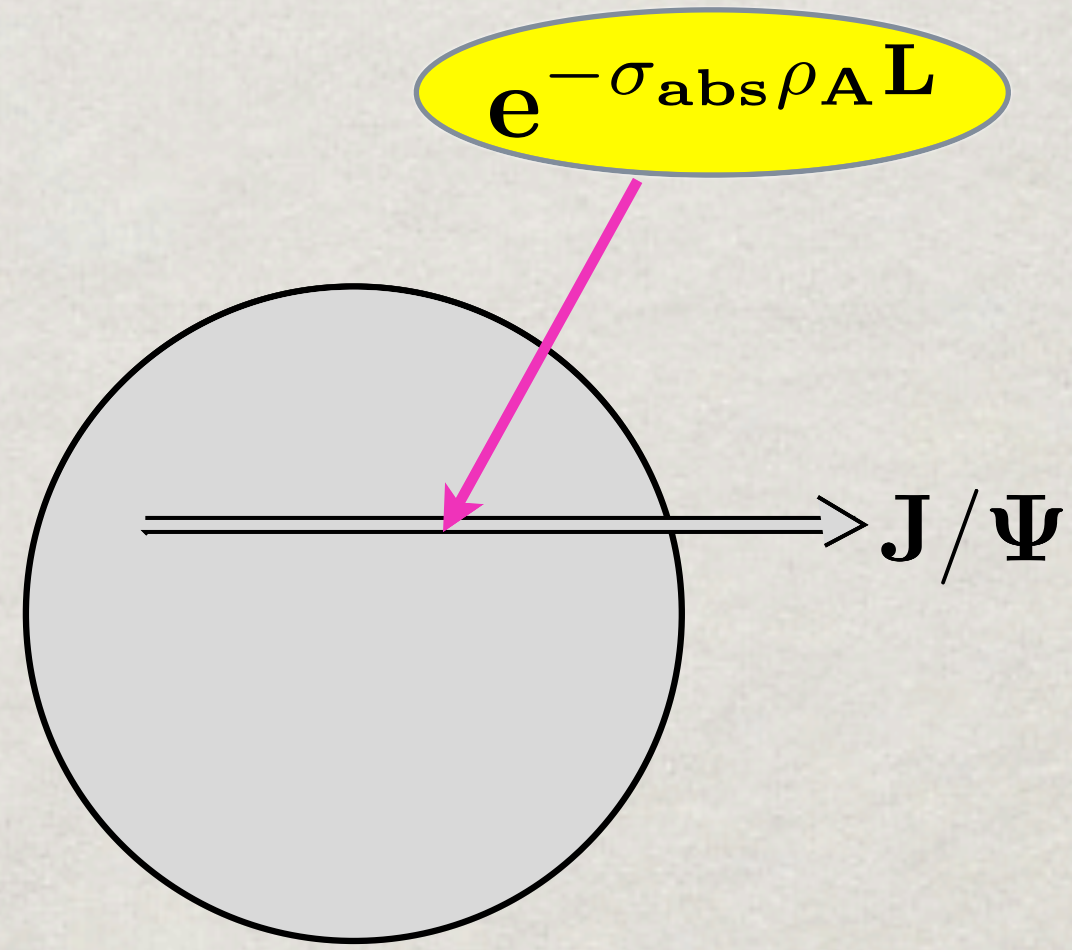
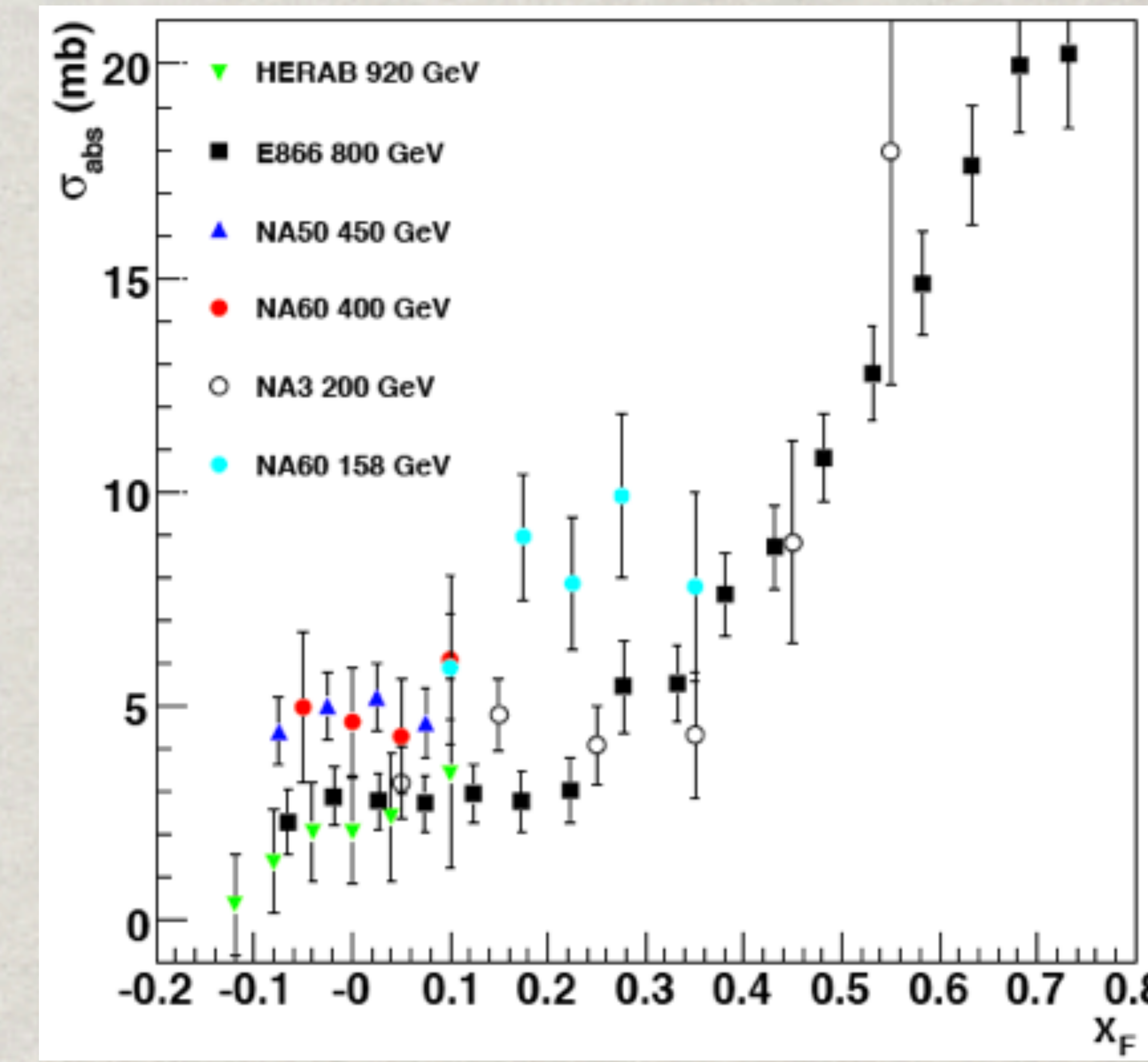
Understanding pA data







NA60:

why does $\sigma_{\rm eff}$ decrease with energy?

The 1st answer: why not?

The 2d answer: no, it doesn't

The 3rd answer: color transparency

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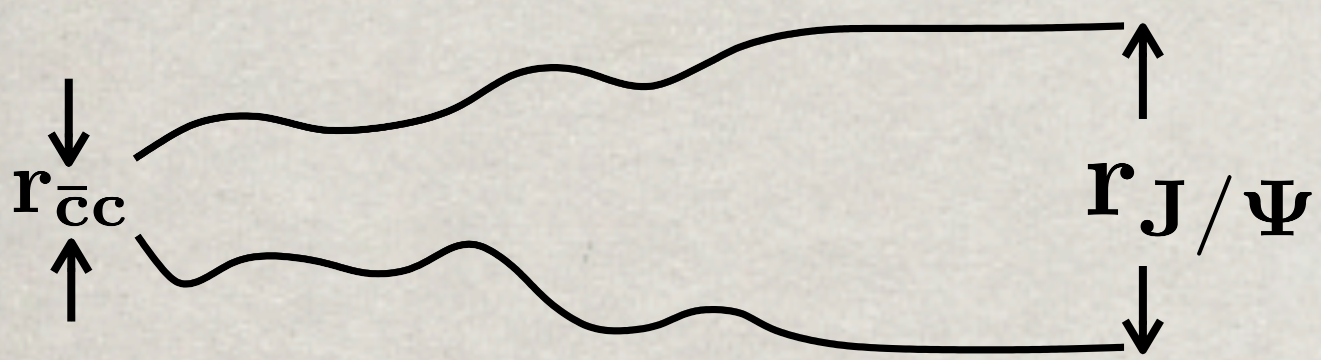
Time scales for J/Ψ production

Color transparency

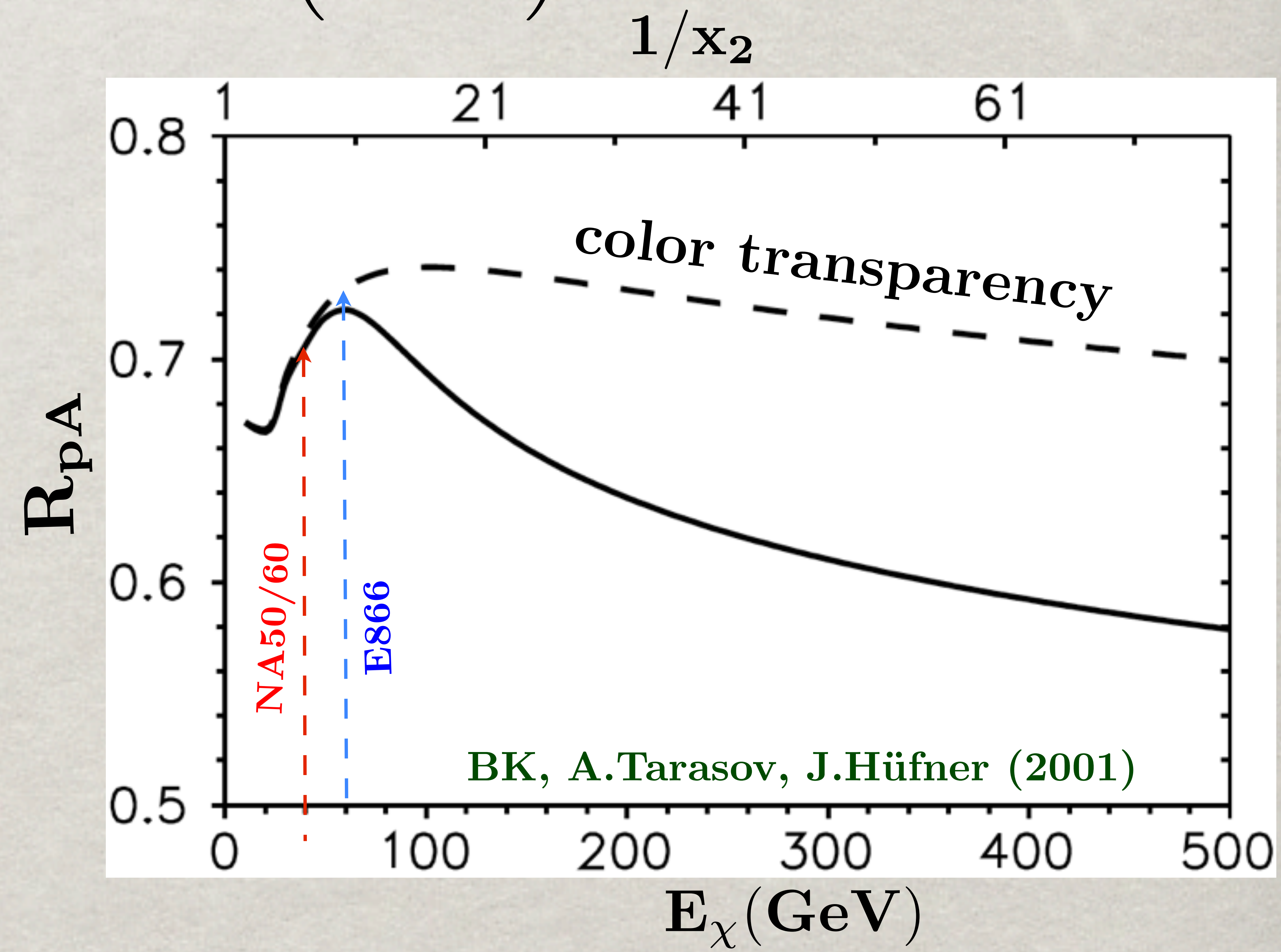
A $\bar{c}c$ dipole is produced with a small separation $r_{\bar{c}c} \sim \frac{1}{m_c} \sim 0.1\mathrm{fm}$

and then evolves into a J/Ψ mean size $r_{J/\Psi} \sim 0.5$ fm

during formation time $t_f = \frac{2E_{J/\Psi}}{m^2_{\Psi'} - m^2_{J/\Psi}} = 0.1\,\mathrm{fm}\left(\frac{E_{J/\Psi}}{1\,\mathrm{GeV}}\right)$



At low J/Ψ energy the dipole quickly expands to J/Ψ, while at high energy Lorentz time dilation keeps the initial small size. So with rising energy σ_{abs} drops, and R_{pA} increases.



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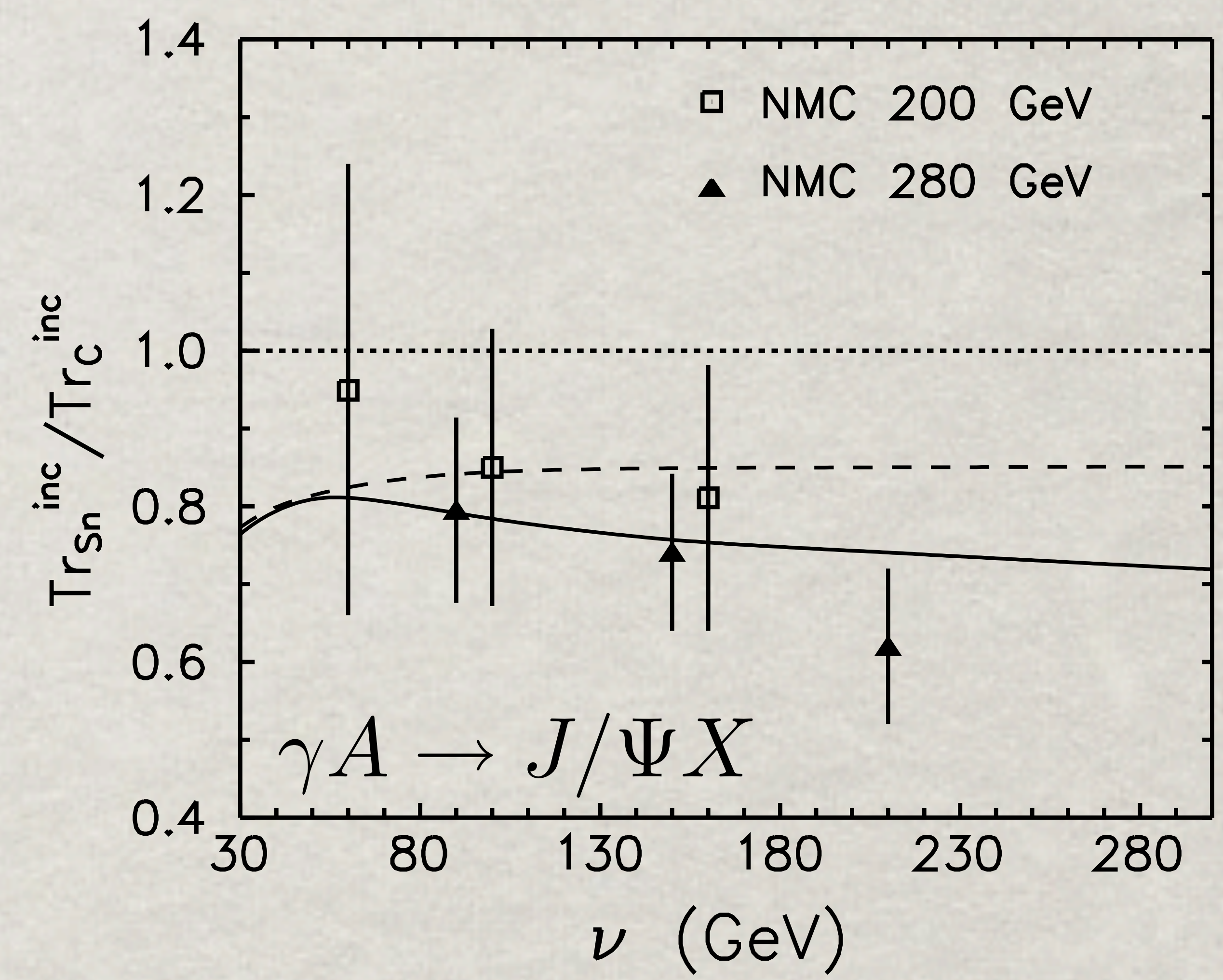
Time scales for J/Ψ production

Quark shadowing

is a higher twist related to the non-zero $\bar{c}c$ separation. Cannot be measured in other processes, but can be well calculated.

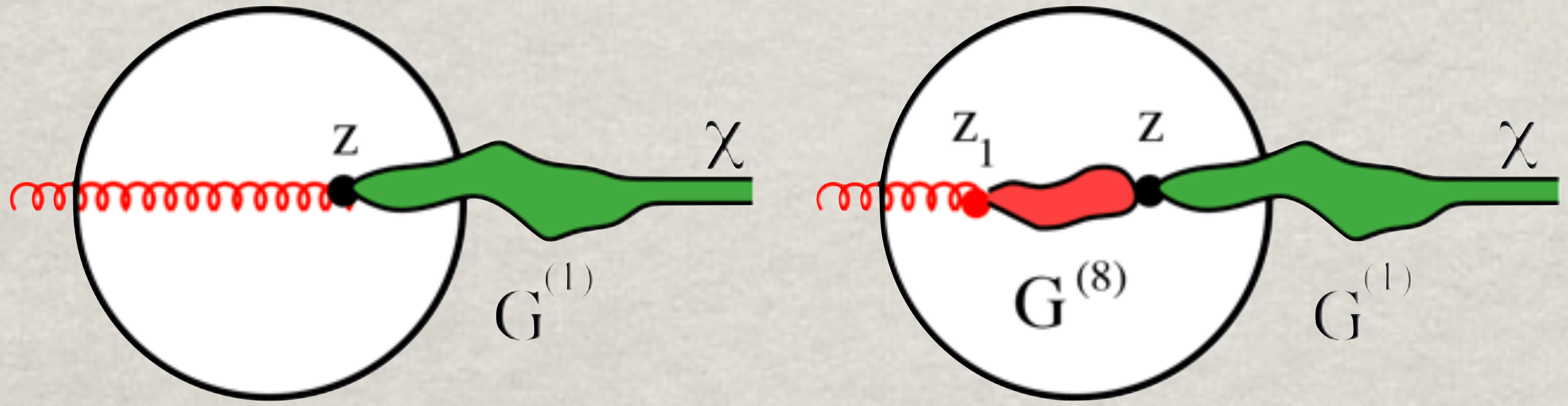


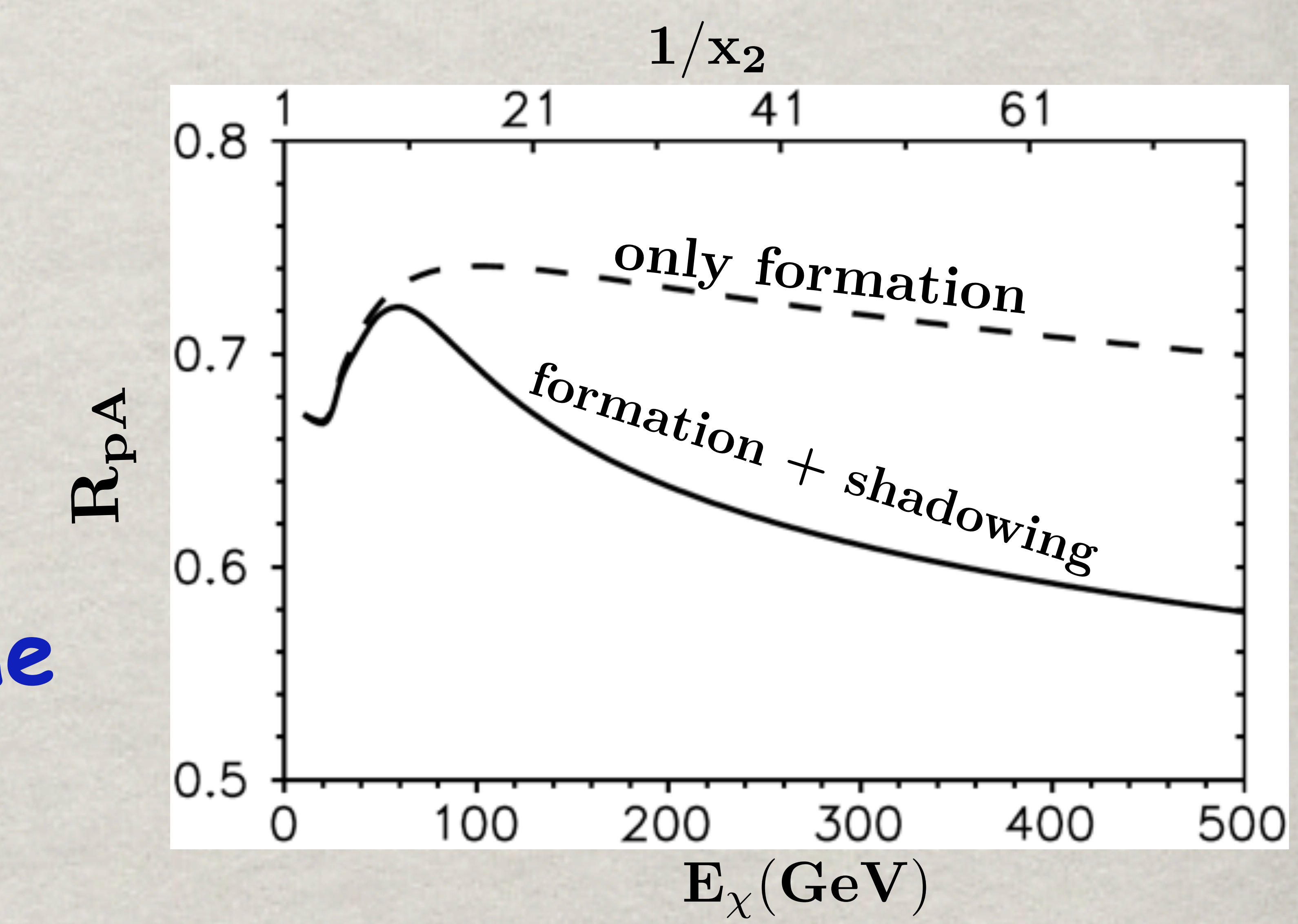
Shadowing onsets when the production time

$$t_p = \frac{2E_{J/\Psi}}{m^2_{J/\Psi}} = \frac{1}{x_2 m_N} \gtrsim R_A$$

(5 times shorter than t_f)

$$p + Pb \to \chi_2 + X$$





Path integral technique: all possible paths of the quarks are summed up. $\sigma_{abs}(r_T)$ gives the imaginary part of the light-cone potential

Time scales for J/Ψ production

Gluon shadowing

The coherence length for gluon shadowing is much shorter than for quarks,

$$l_c^g = \frac{P^g\ s}{m_{J/\Psi}^2 m_N} x_1(1-x_1)$$

$P^g \approx 0.1$ is independent of the scale.

This is why there is no shadowing above $\tilde{x}_2 \gtrsim 0.01$ where $\tilde{x}_2 = x_2/(1-x_1)$

No gluon shadowing in any of the fixed-target experiments on charmonium production. Even at 900 GeV $l_c^g < 1\ \mathrm{fm}$

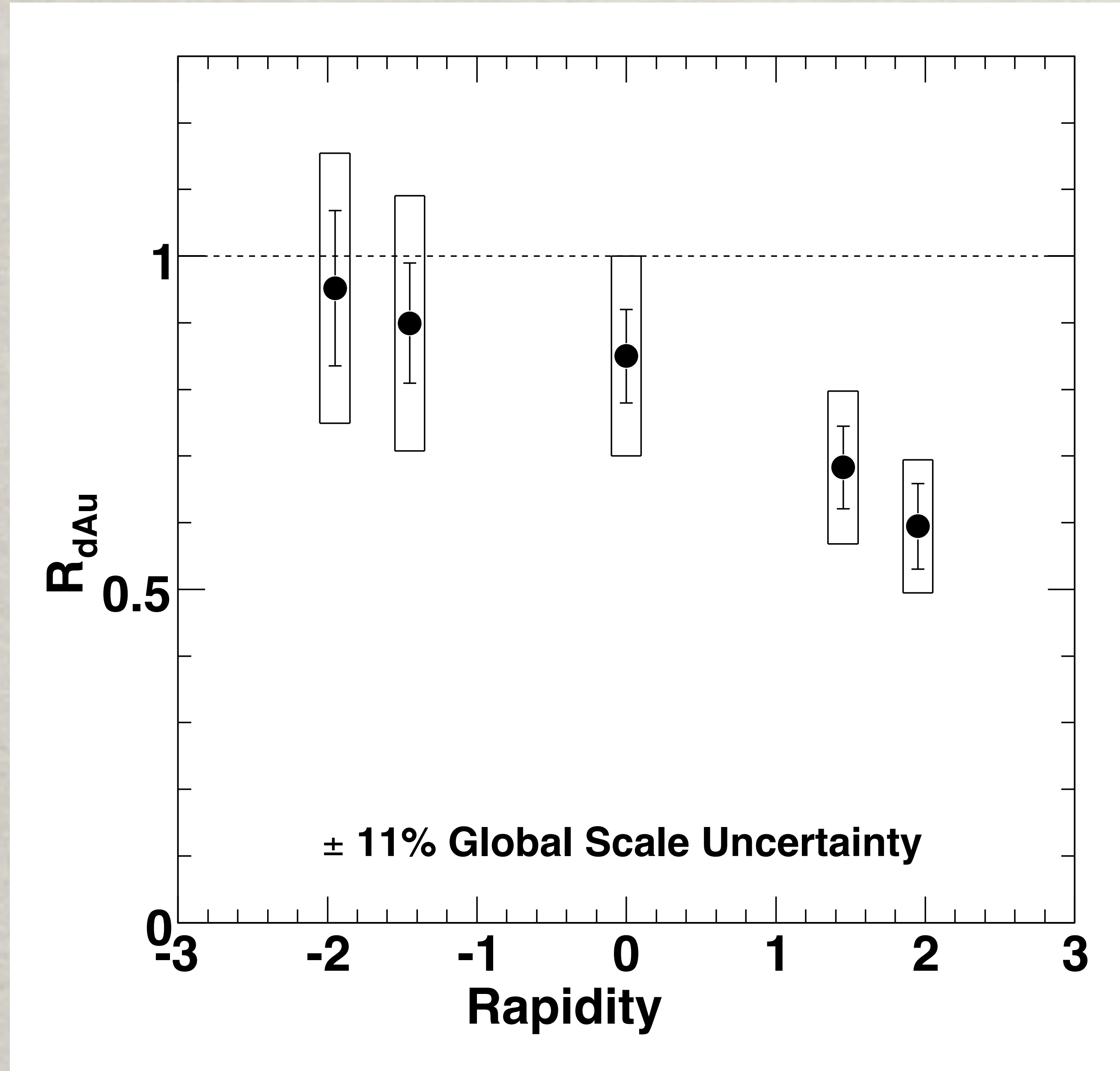
No gluon shadowing at RHIC at $x_F = 0$, since $x_2 \geq 0.018$ is too large.

At forward rapidities x_2 is falling as $x_2 \geq e^{-\eta}\sqrt{(m_{J/\Psi}^2 + \langle p_T^2\rangle)/s}$

At $\eta = 2$ at RHIC $x_2 \geq 0.0025$ (in CSM $\langle x_2\rangle = 0.005$)

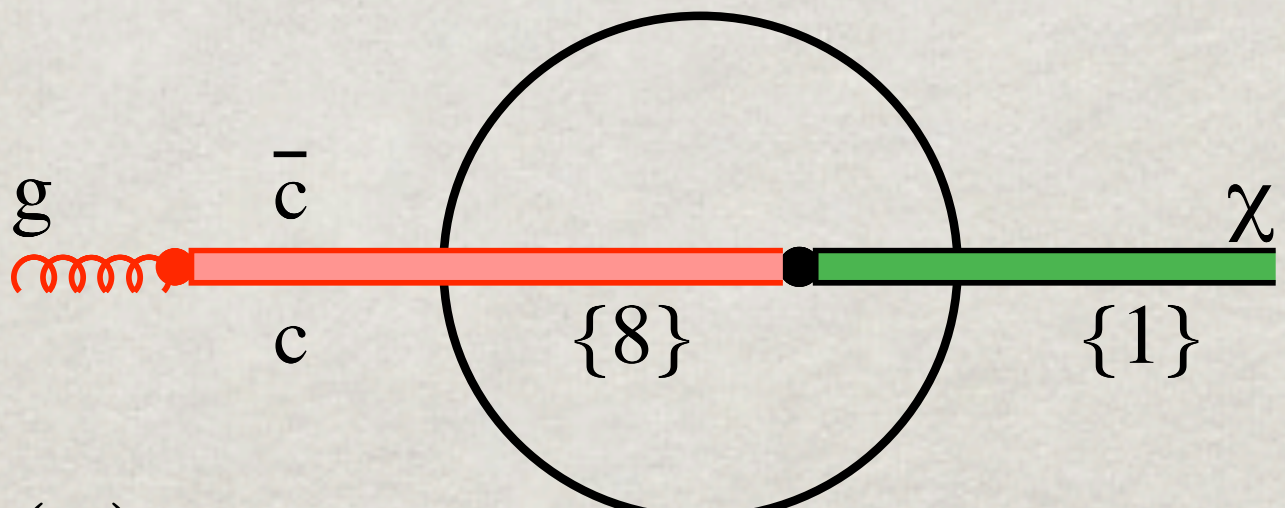
Gluon shadowing is neglidgibly small in the measured rapidity range.

Rapidity dependence at RHIC



Interpretation of this data in terms of a breakup cross section (+ gluon shadowing) is multiply incorrect.

- The $\bar{c}c$ pair attenuates not only in final state (breakup), but also in initial state (shadowing)



$$\sigma_{\bar{c}c}^{(8)} = \frac{7}{16}\,\sigma_{\bar{c}c}^{(1)}$$

- Due to saturation both $\sigma_{\bar{c}c}^{(8)}$ and $\sigma_{\bar{c}c}^{(1)}$ steeply rise with rapidity

$$\boxed{\sigma_{\bar{c}c} \propto Q_s^2(x_2) \propto e^{0.288\eta}}$$

is dictated by DIS data from HERA.

The dipole cross section nearly doubles between η =0 and η =2.

This is sufficient to explain the data

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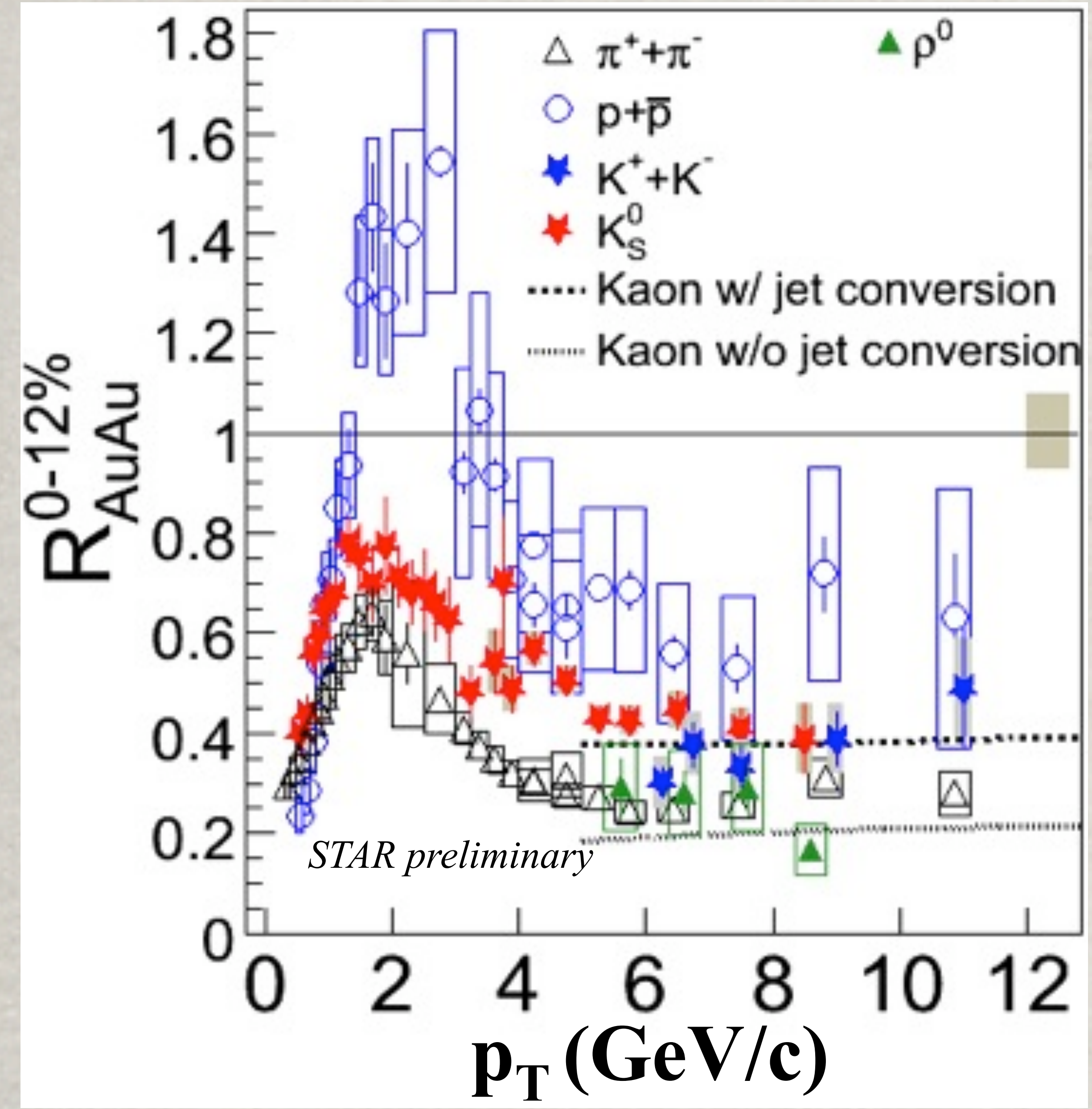
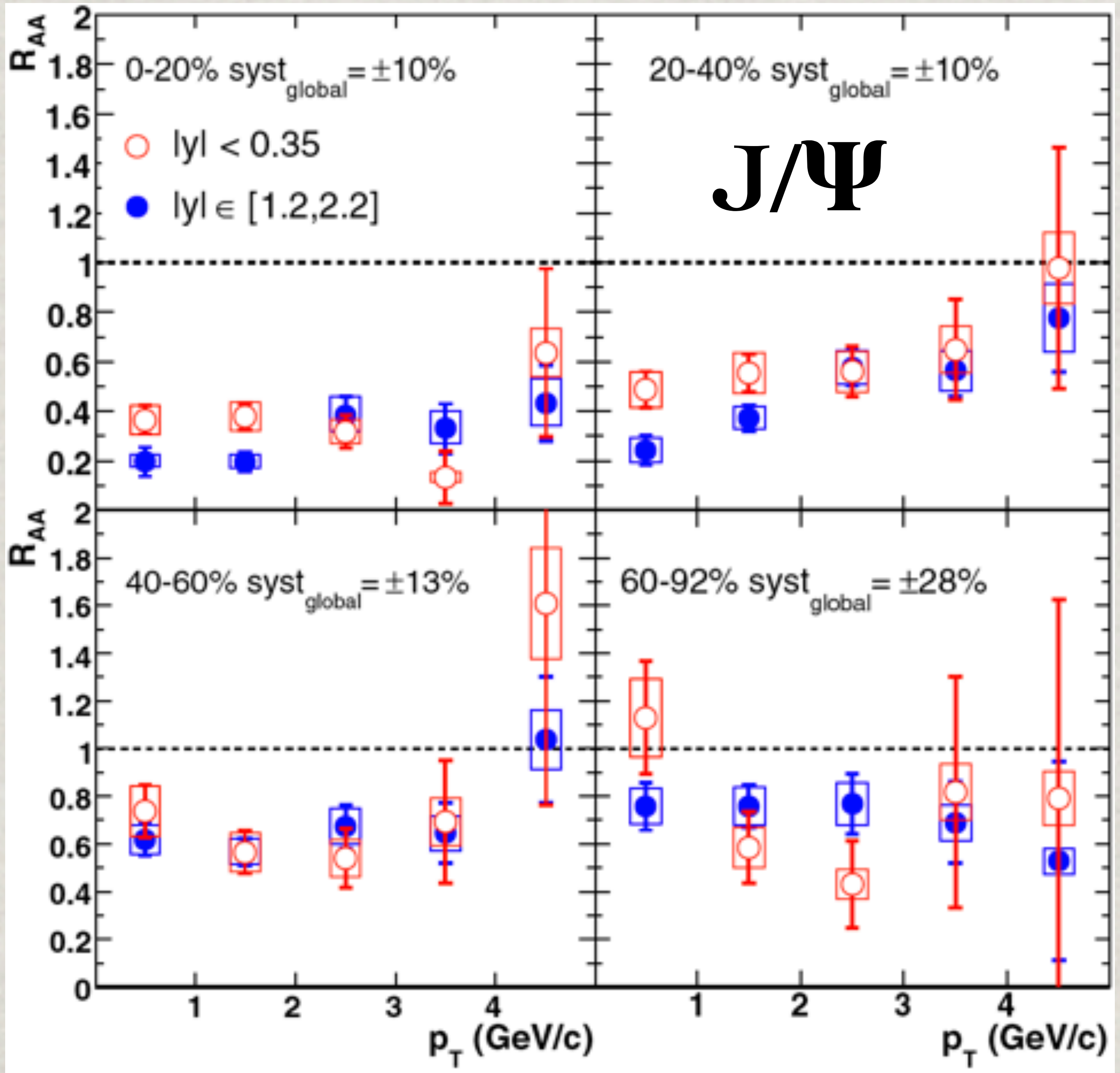
AA collisions: J/Ψ puzzle

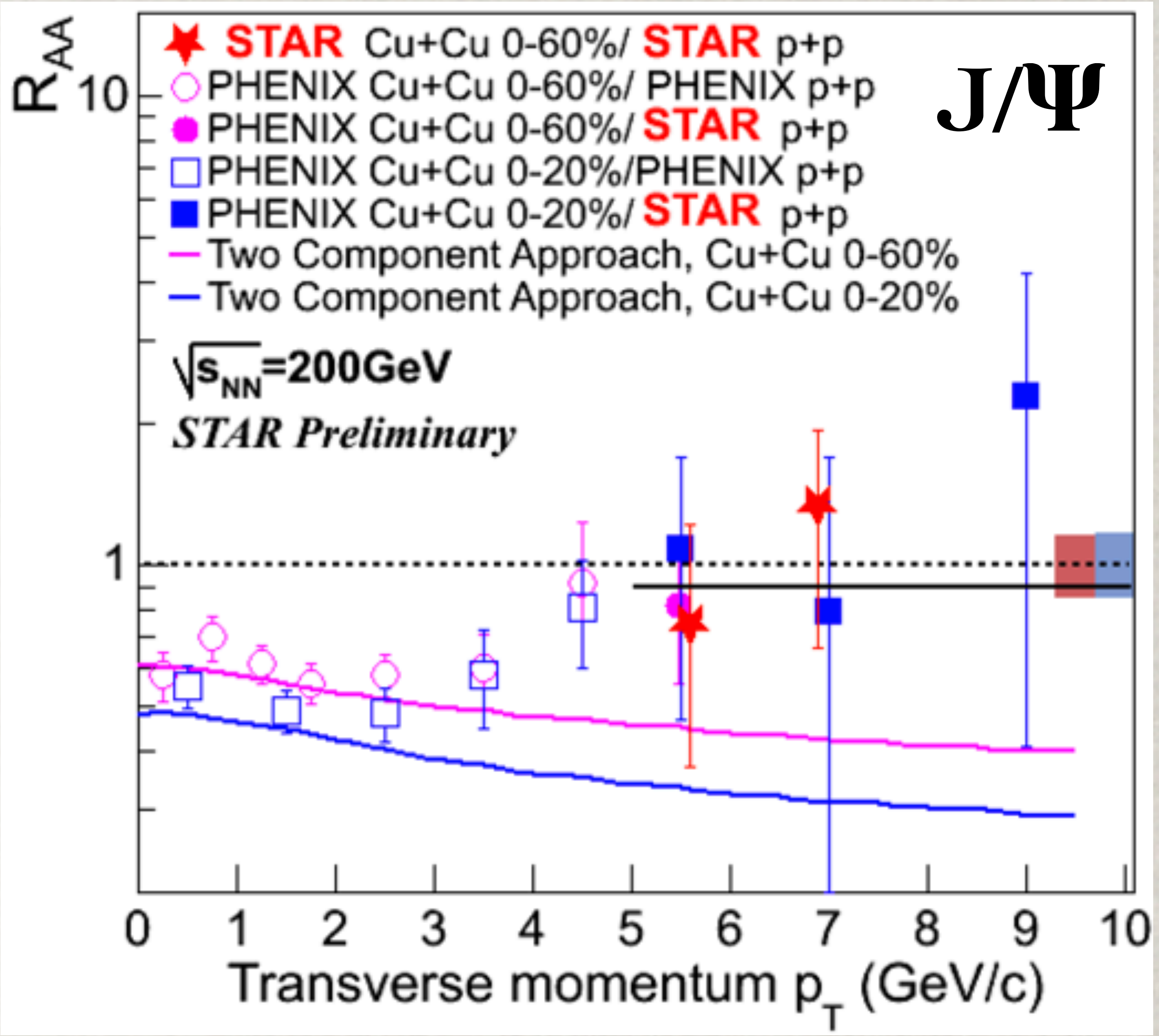
Au-Au



Au-Au



Cu-Cu



The nuclear ratio for all hadronic species has tendency to fall with p_T and then to level off. Only J/Ψ has a trend to rise with p_T

Charmonium is suppressed differently from jets: no energy loss only absorption (breakup)

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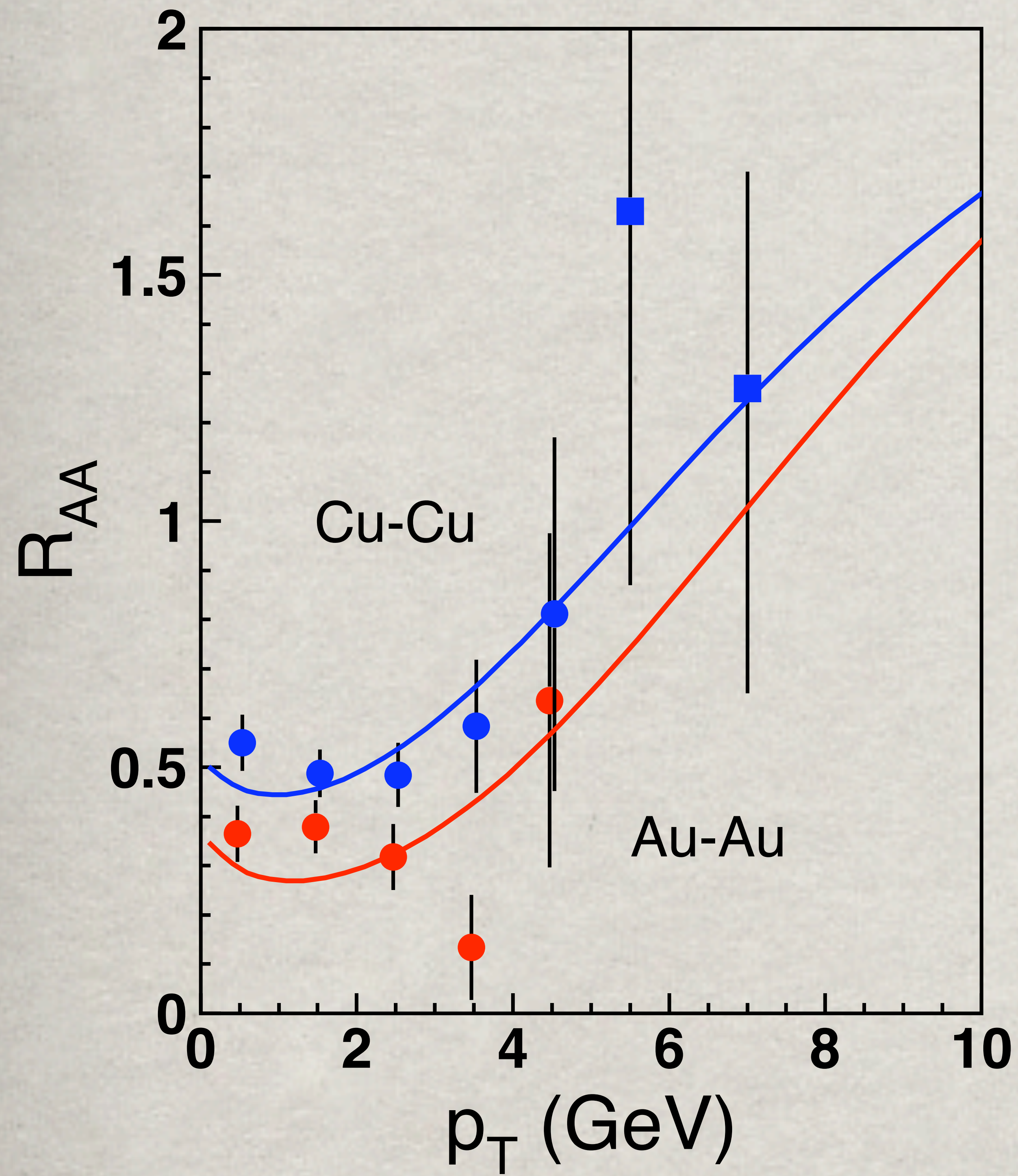
Resolving the puzzle



Three effects, which can be well calculated explain the puzzling behavior of $R_{AA}^{J/\Psi}(p_T)$

- Final state in-medium attenuation of J/Ψ controlled by the transport coefficient $\hat{q}$
- Initial state shadowing/attenuation of the $\bar{c}c$ dipole (not J/Ψ) passing through both nuclei
- Gluon saturation leads to broadening of $\langle p_T^2 \rangle$ of J/Ψ and to a strong Cronin enhancement.

The only fitted parameter is the transport coefficient, which is found to be $\hat{q}_0 = 0.2 - 0.3\ \mathrm{GeV^2/fm}$ smaller than what comes out of jet quenching analyses.

J/Ψ suppression offers a novel way to measure $\hat{q}$

BK, I.Potashnikova, I.Schmidt

Relevant time scales

★ **Production time:**

In the c.m. of the collision a colorless $\bar{c}c$ -pair is produced at the time

$$t_p^* \sim \frac{1}{\sqrt{4m_c^2 + p_T^2}} < 0.07\ \mathrm{fm}$$

which is much shorter that the time scale of medium creation, $t_p \ll t_0$

! However, t_p is $\sqrt{s}/2m_N$ longer in the rest frames of colliding nuclei

★ **Formation time:**

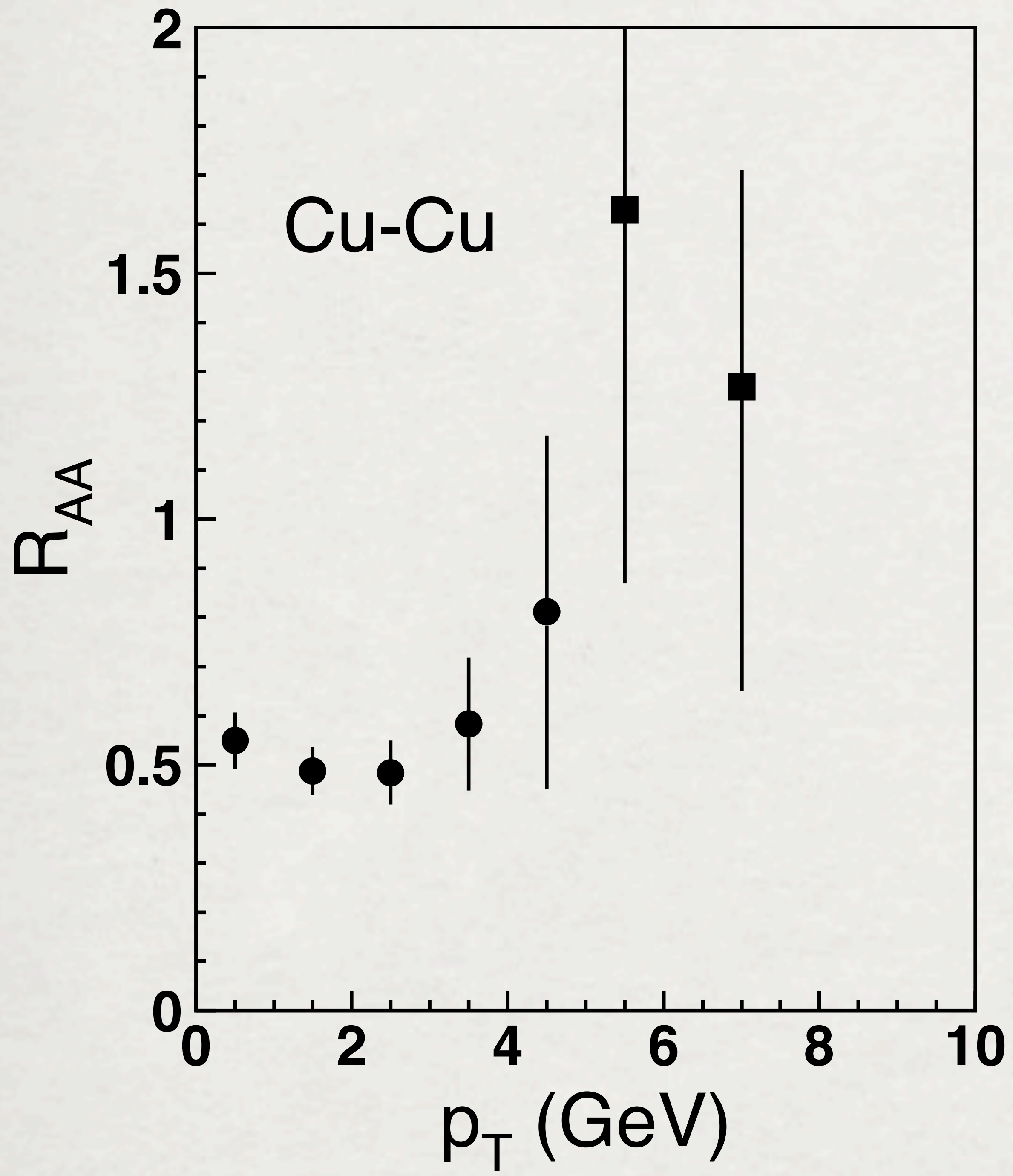
The time of formation of the J/Ψ wave function is also short

$$t_f = \frac{E_{J/\Psi}}{(m_{\Psi'} - m_{J/\Psi})m_{J/\Psi}} \lesssim 0.5\ \mathrm{fm}$$

★ Not a $\bar{c}c$ dipole, but a fully formed J/Ψ propagates through the medium

Nuclear effects

1 Final state attenuation



The absorption cross section for a dipole propagating through a medium is related to the parton broadening, i.e. to the transport coefficient $\hat{q}$

$$\hat{q} = 2\,\rho\,\frac{d\sigma(r)}{dr^2}\Big|_{r=0} \;\rightarrow\; \frac{dS(r,l)}{dl} = -\frac{1}{2}\,\hat{q}\,r^2$$

absorption rate

$$R(s,p_T) = \frac{1}{\pi}\int\limits_0^{\pi} d\phi\,\exp\left[-\frac{1}{2}\,\langle r^2_{J/\Psi}\rangle \int\limits_{l_0}^{\infty} dl\;\hat{q}(\vec{s}+\vec{l})\right]$$

J/Ψ breakup is controlled by the same transport coefficient as the energy loss.

We relied on the popular model $\hat{q}(b,s,t) = \frac{\hat{q}_0\,t_0}{t}\,\frac{n_{part}(b,s)}{n_{part}(0,0)}$, fixed $t_0 = 0.5$ fm

and adjusted $\boxed{\hat{q}_0 = 0.2 - 0.3\ \mathrm{GeV^2/fm}}$ to reproduce the data

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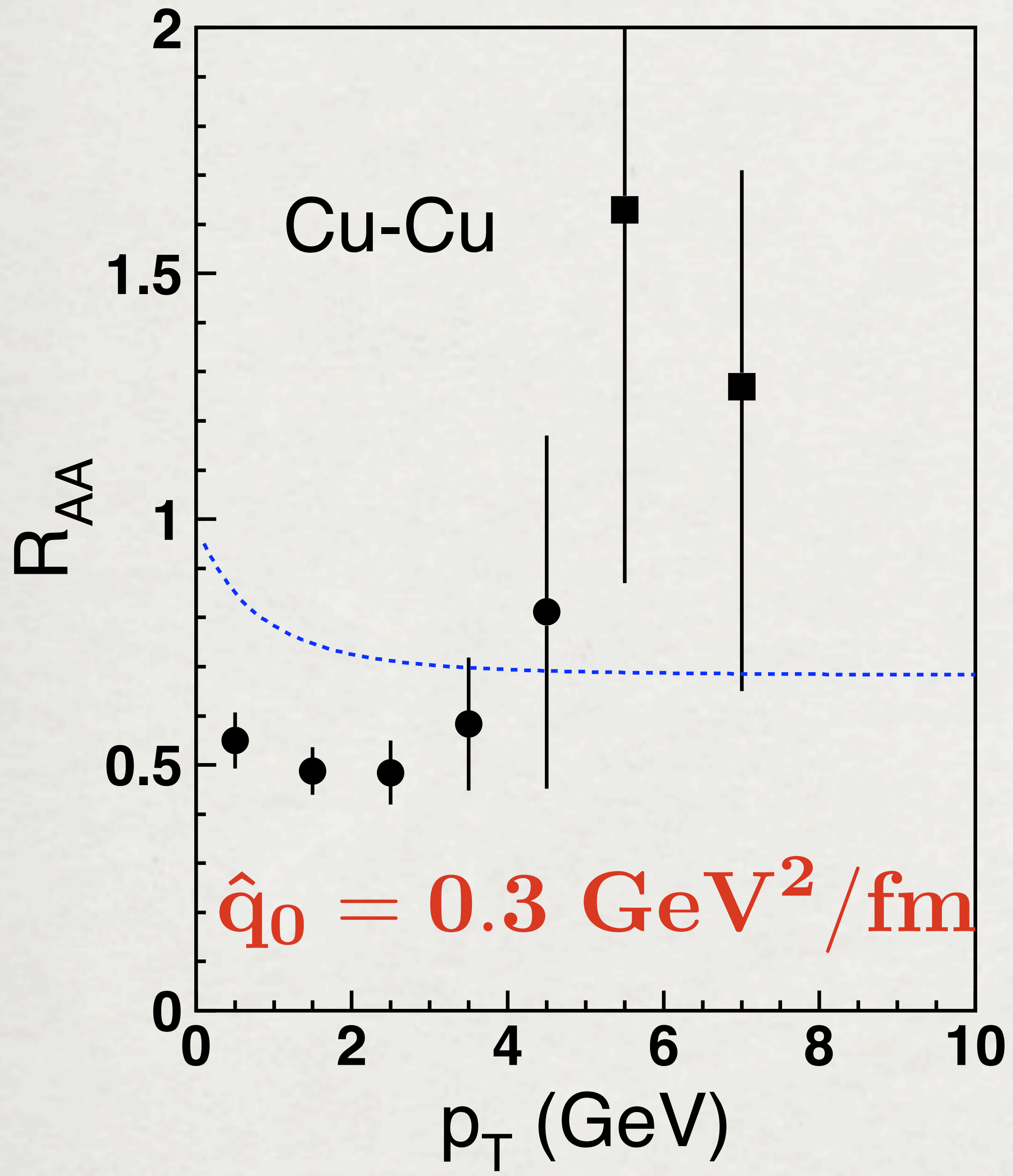

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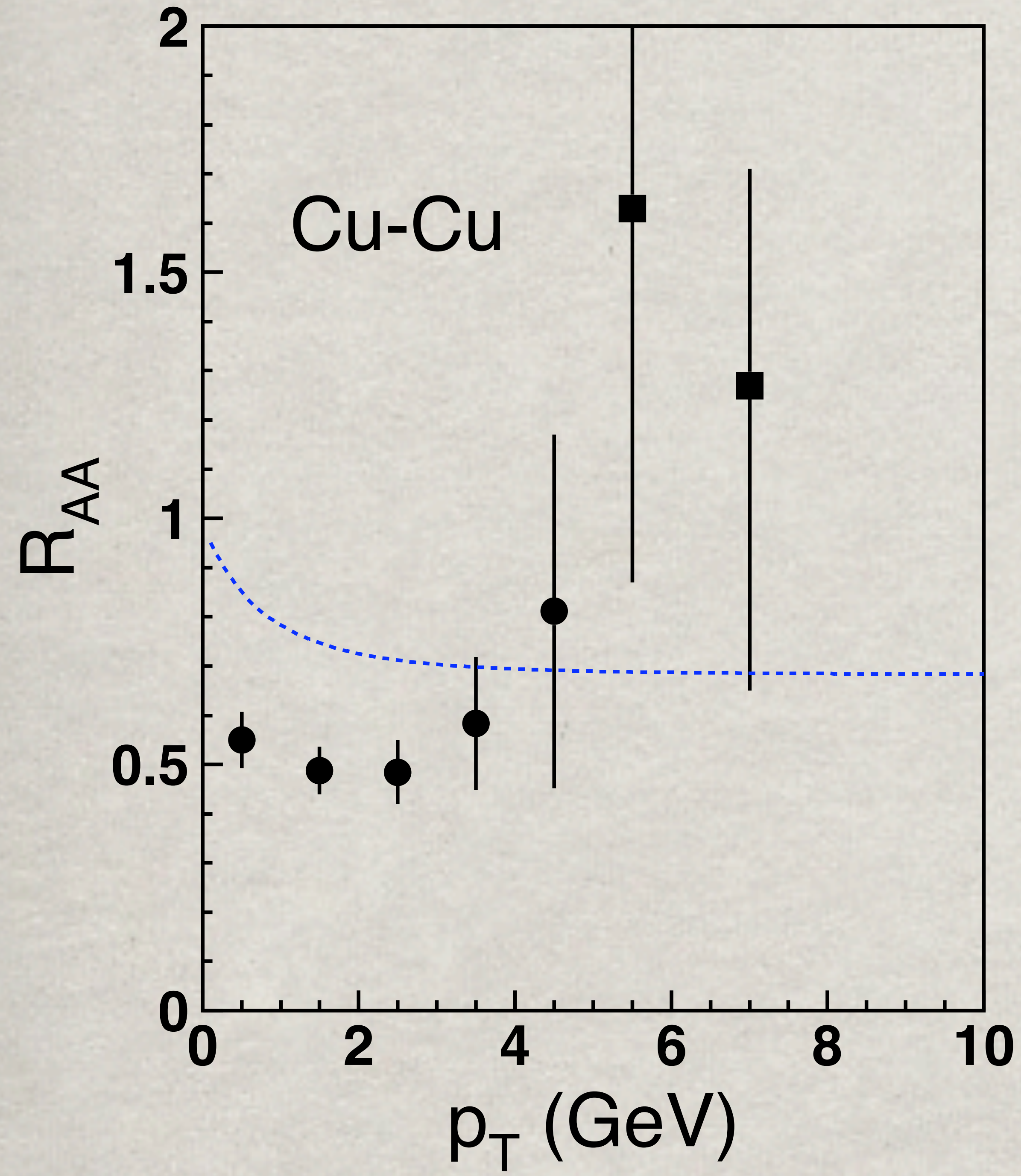
Nuclear effects



2 Initial state suppression

The $\bar{c}c$ production time in the nuclear rest frame

$$t_p^c = \frac{\sqrt{s}}{m_N\sqrt{4m_c^2 + p_T^2}} = \frac{1}{m_N x_2}$$

is sufficient ($5 < t_p < 13$ fm) for quark shadowing.

However, $x_2 > 0.015$ is too large (l_p^g is too short) for gluon shadowing.

Charm shadowing comes together with the breakup cross section, they are not separable. The result, $S_{NA} \approx 0.8$, is known from data. However, the impact parameter dependence is important and can be only calculated.

We assume $S_{AB}(s) = S_{NA}(s)\, S_{NB}(s)$

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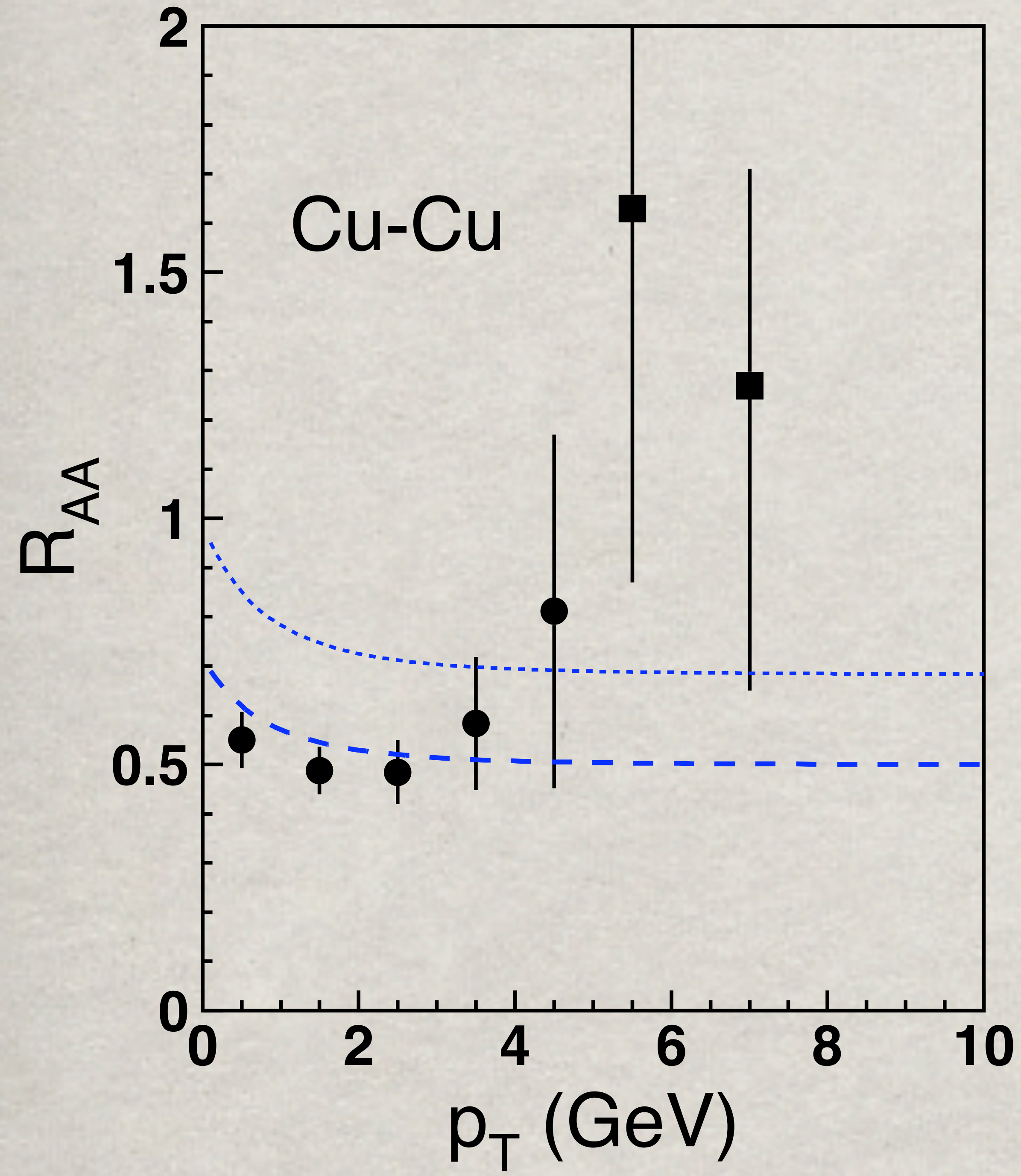
Nuclear effects



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Nuclear effects

3 Initial state saturation of gluons

Due to saturation gluons experience broadening with the coefficient $\mathbf{C(s)}$ known from DIS data.

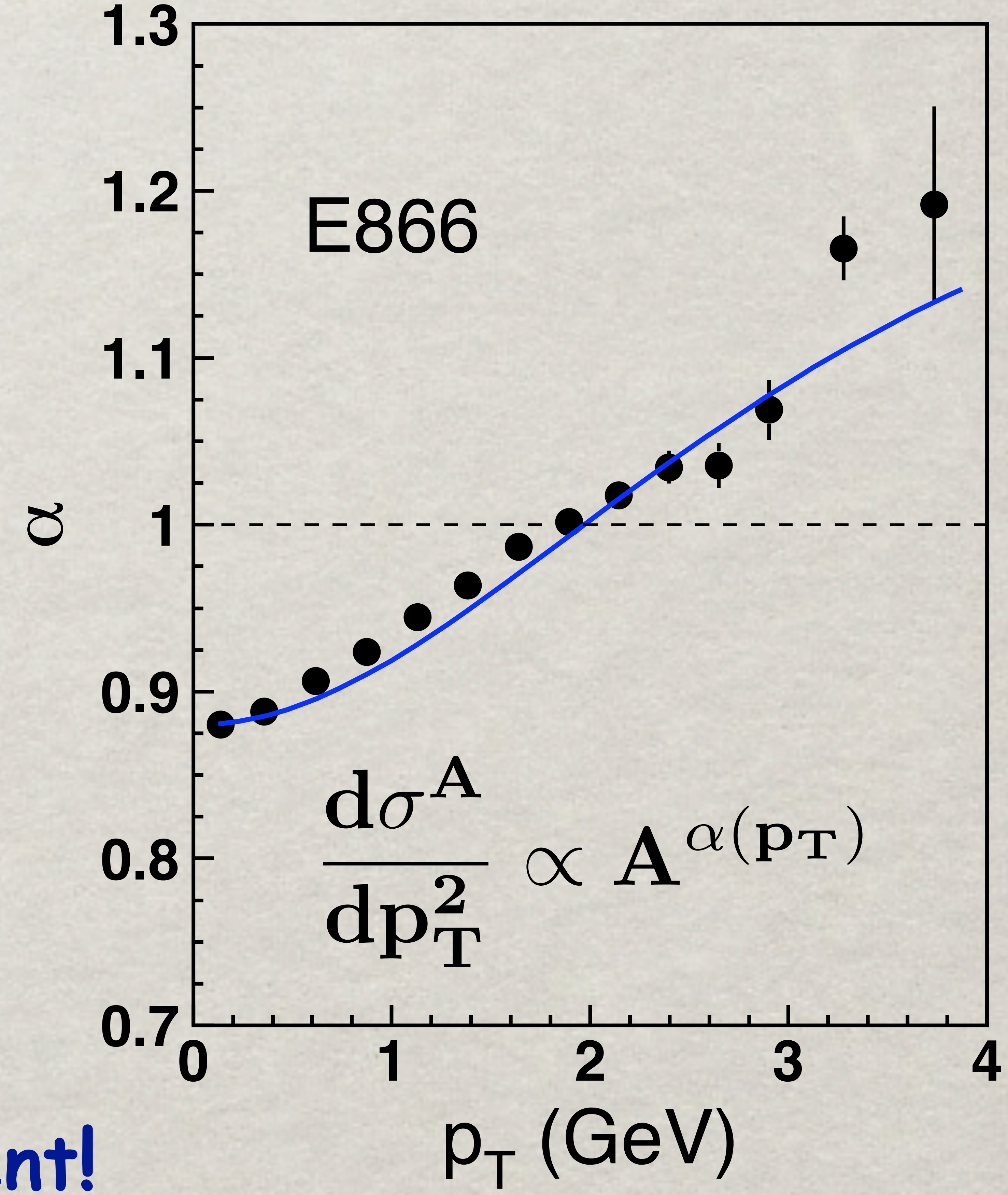
$$\Delta p_T^2 = 2C(s)\,T_A(b)$$

The p_T distribution of J/Ψ has the form:

$$\frac{d\sigma}{dp_T^2} \propto \left(1+\frac{p_T^2}{6\langle p_T^2\rangle}\right)^{-6}$$

Broadening results in $\langle p_T^2\rangle \Rightarrow \langle p_T^2\rangle + \Delta p_T^2$

$$R_T(p_T) = \frac{\left.\frac{d\sigma}{dp_T^2}\right|_{\langle p_T^2\rangle+\Delta p_T^2}}{\left.\frac{d\sigma}{dp_T^2}\right|_{\langle p_T^2\rangle}}$$



★ This can be tested with the E866 data for J/Ψ production in pA at 800 GeV:

Works amazingly well with no adjustment!

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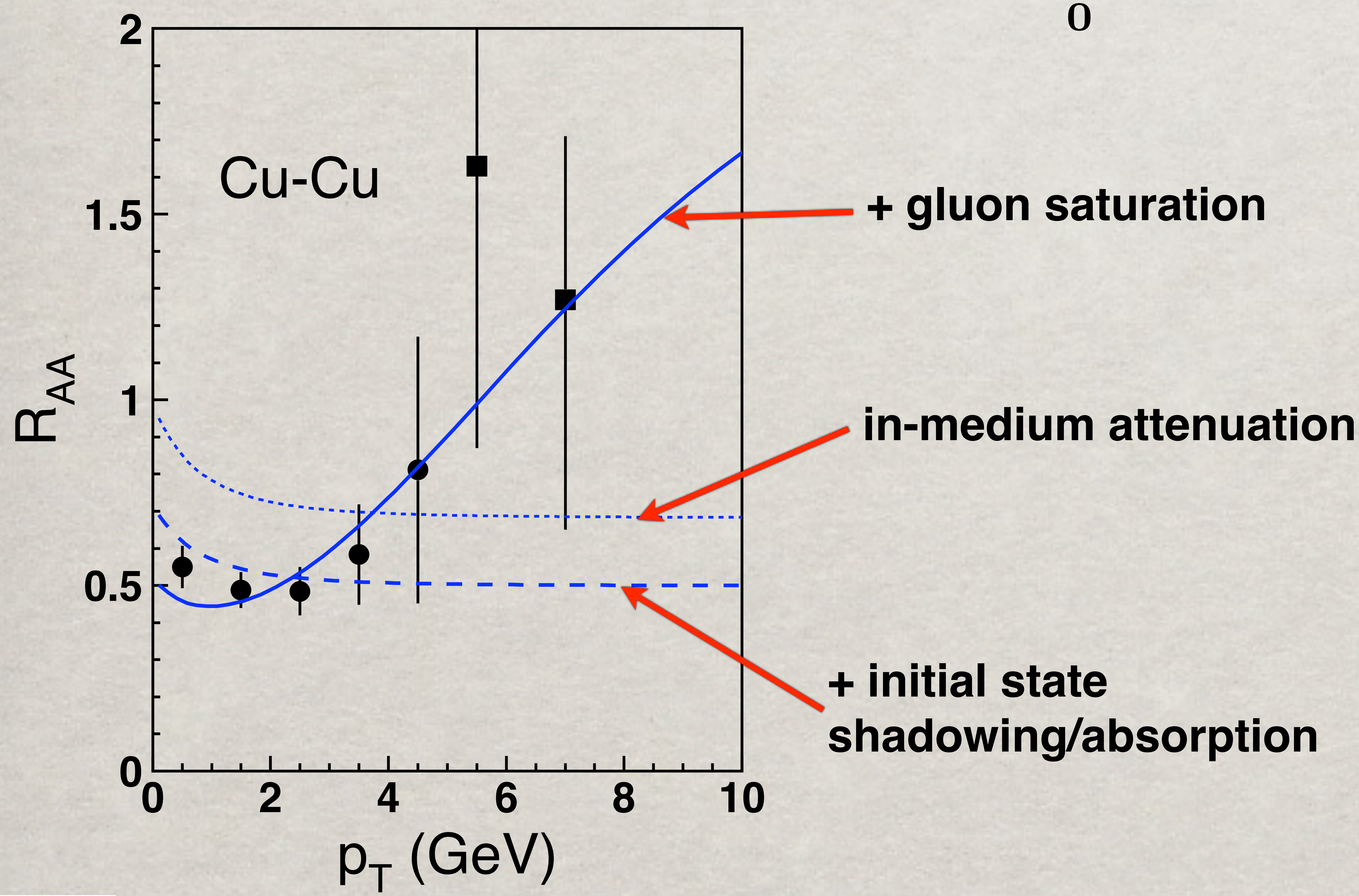
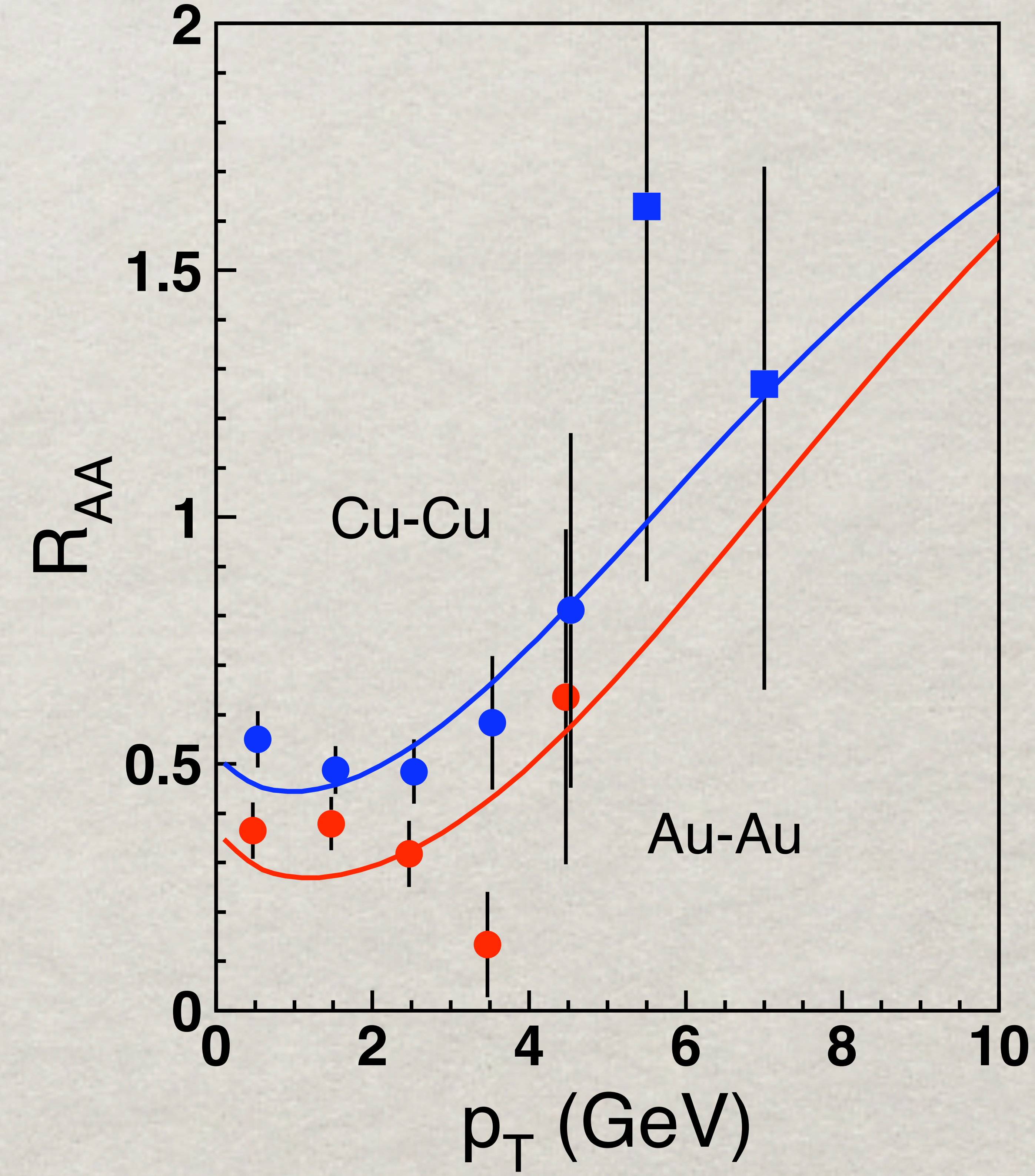
Nuclear effects

Eventually, combining all three mechanisms we arrive at the final result

$$R_{AA}^{J/\Psi}(p_T) = \frac{\int\limits_0^\infty ds^2\, T_A^2(s)\, R(s,p_T)\, S_{AA}(s)\, R_T(s,p_T)}{\int\limits_0^\infty ds^2\, T_A^2(s)}$$





Summarizing,

Charmonium production offers a novel clean probe for the medium created in heavy ion collisions:

No energy loss, no coherence effects for a charmonium propagating through the medium. Attenuation is controlled by the transport coefficient which is found to be small, $\hat{q}_0 = 0.2 - 0.3\ \mathrm{GeV^2/fm}$, compared to the results if jet quenching analyses based on the energy loss scenario.

If any additional source of nuclear suppression was missed, that may lead only to a reduction of $\hat{q}_0$

Production of other charmonia and bottomia should be a good test and bring forth more information